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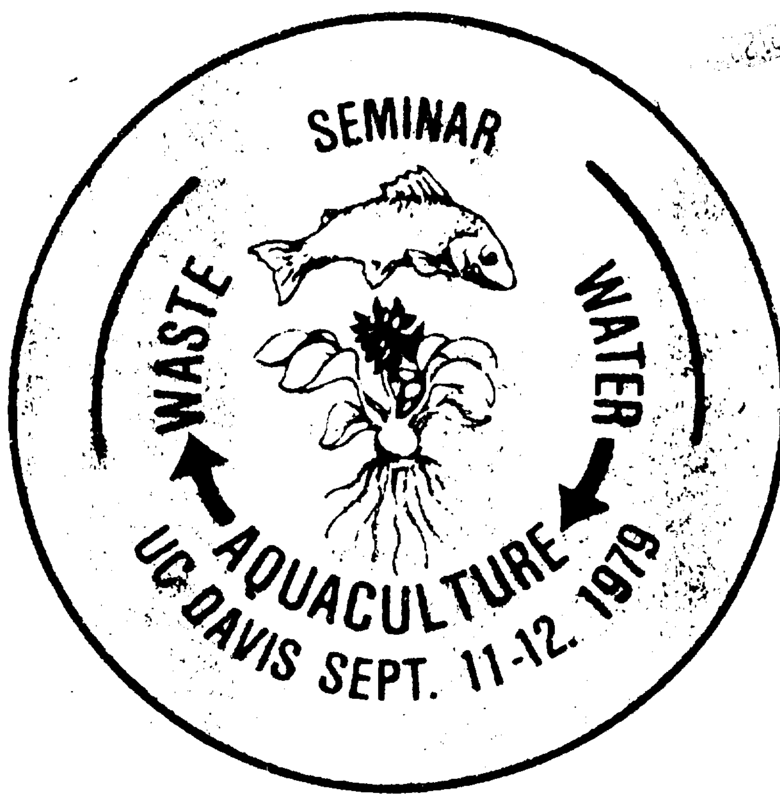
Aquaculture Systems for Wastewater Treatment

Seminar Proceedings and Engineering Assessment



Aquatic Plant Processes Session

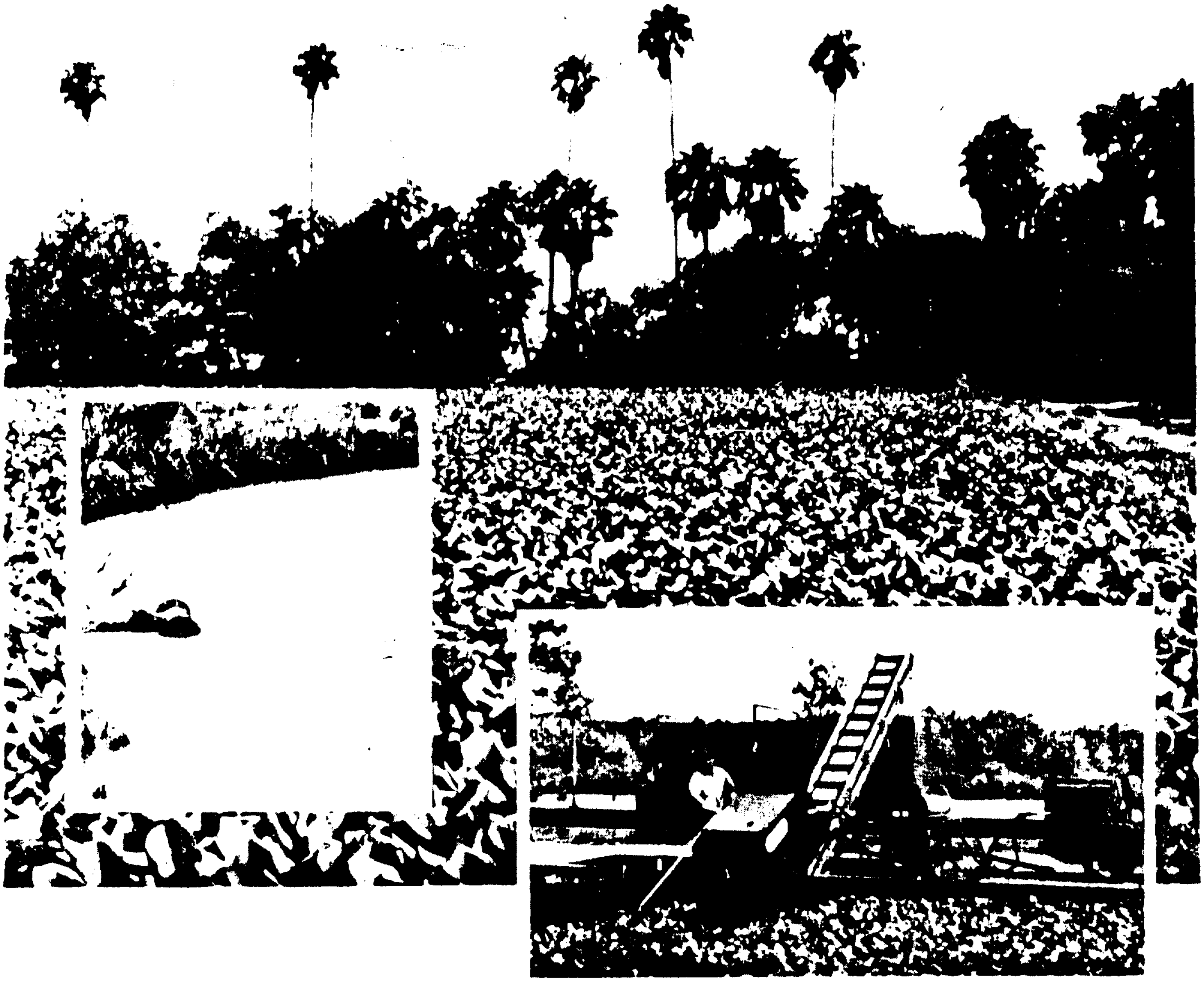


Photo of a large pond in San Juan, Texas covered by water
yacinths to help improve water quality. Inserts depict water
yacinths being harvested from the Disneyworld water hyacinths
isting facility at Lake Buena Vista, Florida and a duckweed
overed treatment pond near North Biloxi, Mississippi.

AQUATIC PLANT PROCESSES: SESSION SUMMARY

Presentations in this session covered wastewater treatment utilizing vascular aquatic plants with water hyacinth (Eichhornia crassipes) being the predominate plant discussed. The potential of more cold tolerant plants such as duckweed for treating domestic wastewater was briefly discussed.

Results of these studies clearly demonstrate the potential of higher plants in both domestic and industrial wastewater treatment. Wastewater lagoons are the most popular and inexpensive method of treating domestic wastewater in small communities. Data on upgrading sewage lagoons in Mississippi and Texas presented during the seminar demonstrated the potential for using this technology for improving the performance of lagoons located in warmer regions of the United States. Potential problems associated with using water hyacinth to upgrade sewage lagoons were identified along with suggested solutions.

When plant coverage is complete, single cell lagoons with BOD_5 loading rates in excess of 40 kg/ha/day without aeration are subject to producing odors, especially at night when the plants are not photosynthesizing. Multicelled lagoons with surface aerators in the raw sewage cell and single cell lagoons with maximum BOD_5 loading rates of 30 kg/ha/day are the best candidates for upgrading these lagoons using water hyacinth or duckweed.

Data on the use of water hyacinth for tertiary treatment in Florida was presented. The data suggest that all parameters for tertiary treatment with the possible exception of phosphorus can be met in south Florida using approximately one acre of water hyacinth per 379 m^3/day of wastewater effluent from an activated sludge plant. Because the ratio of N:P in water hyacinth plant tissue is approximately 6:1 and the ratio in wastewater approximately 3:1, nitrogen is depleted first and becomes a limiting factor before the phosphorus is reduced below 1 mg/l.

Engineering data was also given for designing optimal water hyacinth and duckweed sewage treatment systems to achieve secondary and possibly tertiary treatment quality in small communities.

B. C. Wolverton

B. C. Wolverton, Ph.D.
4/28/80

ENGINEERING DESIGN DATA FOR SMALL VASCULAR AQUATIC PLANT WASTEWATER TREATMENT SYSTEMS

B. C. Wolverton, National Space Technology Laboratories, ERL, NASA, NSTL Station, Mississippi 39529

A general background of the research findings of the National Aeronautics and Space Administration's Vascular Aquatic Plant Program using higher plants such as the water hyacinth (*Eichhornia crassipes*) and duckweed (*Lemna* sp. and *Spirodela* sp.) to treat domestic wastewater is presented. New data on a small two cell lagoon system using only duckweed is included. Further laboratory experiments were conducted to correlate BOD_5 removal with known wet masses of water hyacinths. The data from these experiments with domestic wastewater indicates that an average total BOD_5 removal rate of 4.0 mg BOD_5/gram WW (wet weight) could be achieved with a seven day retention time. When a phenol solution is substituted for the wastewater, the average total BOD_5 removal is 3.5 mg BOD_5/gram WW (wet weight) in seven days. This data along with the results of the previous field experiments is used to develop design criteria for small domestic wastewater treatment systems servicing a maximum of 3,000 people. The criteria for these systems addresses the problems of BOD_5 reduction, total suspended solids reduction, odor control, and sludge accumulation.

INTRODUCTION

In the United States, wastewater lagoons are the most popular and inexpensive method of treating domestic wastewater in small communities. Thousands of these lagoons exist throughout the United States for treating domestic sewage and various type animal and industrial wastewaters. Wastewater treatment lagoons vary from single to multiple celled systems. Some of the earlier sewage lagoons were improperly designed and constructed causing short circuiting, reducing the effective detention time and contributing to high BOD and suspended solids in the lagoon effluent. Today sufficient information is available to provide a basis for rational design and construction of wastewater treatment lagoons. For in depth information on wastewater treatment lagoons see Gloyna,[1] Middlebrooks[2] and Oswald.[3,4] Lagoon systems constructed in recent years are usually effective in BOD reduction; however, excess algae can still cause high suspended solids in the lagoon effluent during warm, summer months.

NASA at the National Space Technology Laboratories (NSTL) has been using higher plants for five years to upgrade wastewater treatment lagoons and treat chemical wastewaters.[5,6,7] NSTL has also been conducting studies directed toward using higher plants to recycle waste in future space stations. The controlled use of higher plants such as water hyacinths (*Eichhornia crassipes*) and duckweeds (*Spirodela* sp., *Lemna* sp. and *Wolffia* sp.) in conjunction with waste stabilization ponds not only increased the BOD removal capacity of these systems, but also reduced the high total suspended solids normally associated with sewage lagoons. Higher plants reduce suspended solids in lagoon effluents by reducing algae which make up a large portion of the suspended solids. Nitrogen, phosphorus, potassium, sulfur, calcium and other minerals can be removed from domestic sewage by harvesting the plant biomass. This harvested plant material is also a potential source of energy, fertilizer, feed, food and other products.

One important question about the design of vascular aquatic plant waste treatment systems that has not fully been determined or fully understood yet is the BOD removal rate that can be expected for this type system. The experiments in this report were designed to address this unknown and achieve reproducible and quantitative answers to this question. Results of these experiments and previous field studies were combined to develop design parameters for energy-efficient waste treatment systems for small communities using vascular aquatic plants.

BACKGROUND

In addition to upgrading all wastewater treatment systems at NSTL using water hyacinths and duckweeds, NASA has conducted several field studies with local communities in South Mississippi directed toward improving their lagoon systems using higher plants. Systems described here will include two single cell lagoons, one at NSTL and one at Lucedale, Mississippi, and two multi-cell lagoons at Orange Grove and Cedar Lake developments at Gulfport and Biloxi, Mississippi, respectively.

The single cell lagoon at NSTL has a surface area of 2 hectares and an average depth of 1.22 meters. The average flow rate of 475 m^3/day resulted in a detention time of approximately 54 days. The BOD_5 loading rate in this lagoon averages 26 kg/ha/day, which constitutes a relatively light load. Before water hyacinths were added to this lagoon, the raw sewage entering at the center of the system averaged 91 mg/l BOD_5 and 70 mg/l total suspended solids (TSS) with effluent averages of 17 mg/l BOD_5 and 49 mg/l TSS. Concentrations of BOD_5 and TSS during a 14 month water hyacinth covered study period were: influent BOD_5 110 mg/l and TSS 97 mg/l, and effluent BOD_5 7.4 mg/l and TSS 10 mg/l.[6] Plants harvested from this lagoon contained 2.73% kjeldahl nitrogen and 0.45% total phosphorus (dry plant weight).

A single cell facultative lagoon located at Lucedale, Mississippi was studied extensively with and without water hyacinth coverage.[8] This lagoon has a surface area of 3.6 hectares (9 acres) and an average depth of 1.73 meters. Lagoon effluent flow rates during 100% water hyacinth coverage averaged 935 m^3/day. The BOD_5 loading rate was 44 kg/hectare/day. Before water hyacinths were added to this lagoon, the raw sewage entering averaged 127 mg/l BOD_5 and 140 mg/l TSS with effluent averages of 57 mg/l BOD_5 and 77 mg/l TSS. Concentrations of BOD_5 and TSS during the study period with complete plant coverage were: influent, 161 mg/l BOD_5 and 125 mg/l TSS; effluent, 23 mg/l BOD_5 and 6 mg/l TSS. With complete water hyacinth coverage this lagoon was almost entirely anaerobic with only traces of dissolved oxygen near the surface in the plant root zone. This condition produced odors at night when the plants were not photosynthesizing. The BOD_5 loading rate of 44 kg/hectare/day produced odors at night from this lagoon; whereas, a loading rate of 26 kg/hectare/day in the NSTL lagoon produced a relatively odor free system when covered with water hyacinths. Plants harvested from this system contained 3.56% kjeldahl nitrogen and 0.89% total phosphorus (dry plant weight).

A complex lagoon system at Orange Grove, Mississippi was used for conducting a 12 month study with water hyacinths in effluent from aerated lagoons.[9] This system consisted of two large aerated lagoons followed by three parallel unaerated lagoons. The flow rate into the water hyacinth covered lagoon averaged 1000 m^3/day. This lagoon had a surface area of 0.28 hectare and an average depth of 1.83 m. The flow rate resulted in an average detention time of 6.8 days. The BOD_5 of the influent entering this lagoon averaged 50 mg/l with an annual effluent average of 14 mg/l. The total suspended solids entering averaged 49 mg/l with an effluent average of 15 mg/l. A parallel, control lagoon without water hyacinth demonstrated effluent concentrations of 37 mg/l BOD_5 and 53 mg/l TSS. Freezing temperatures occurred during this 12 month study period killing the tops of the plants, and the decay of this large amount of biomass elevated the BOD_5 and TSS levels in the effluent during the months of January, February, and March. However, the water hyacinth covered lagoon still maintained the low effluent BOD_5 and TSS averages well below the permit levels of 30 mg/l each. Because of the 1.83 m (6 ft) depth, the dissolved oxygen averaged 2.0 mg/l in the effluent but was increased to 5 mg/l following a 0.91 m (3 ft) drop to a drainage ditch. Plants harvested from this system contained a 3.74% kjeldahl nitrogen and 0.85% total phosphorus (dry plant weight). Evapotransporation rates can be expected to reach as high as 40% of the total influent volumes per day during hot summer months. This characteristic was not considered in the interpretation of these field studies; therefore, the effluent BOD_5 and TSS concentrations should be up to 40% less during the summer months.

A fourth system which is still being studied is a two cell lagoon system located at Cedar Lake development in North Biloxi, Mississippi. This system shown in Figure 1 has been in operation for 9 years. It has been receiving its present load of approximately 49.2 m^3/day (13,000 gal/day) from 51 homes for 7 years. This system was designed as a conventional, two cell lagoon with aeration in the first cell. The first cell has a surface area of approximately 0.08 hectare (0.20 acre) and an average depth of 2.4 m (8 ft). The average flow rate of 49.2 m^3/day results in a detention time of approximately 36 days. The BOD_5 loading in this lagoon is approximately 128 kg/ha/day (114 lb/ac/day). The second cell has a surface area of 0.07 hectare (0.18 acre) and an average depth of 1.5 m (5 ft) with a detention time of approximately 22 days. Four years ago duckweed coverage of the second, unaerated cell occurred through natural means, and NSTL started monitoring this system in April 1979. Prior to this date monitoring had not been conducted; therefore, background data without duckweeds is not available at this time. In May approximately 50% of the duckweed coverage was removed for the first time in four years. The 5 hp surface aerator in the first cell was reduced to operating only at night. From May to December 1979 (see Table 1)

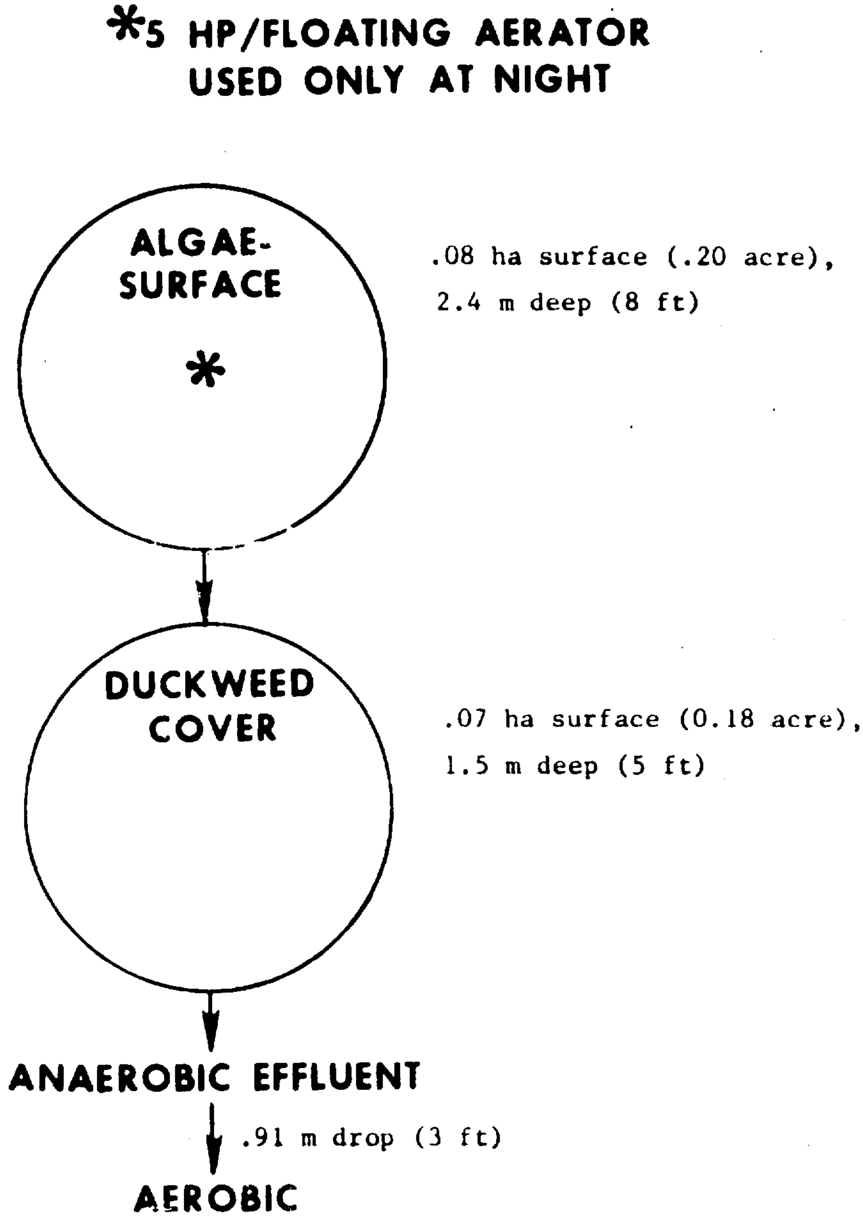


Figure 1. Sewage Lagoons Serving Approximately 200 People--Cedar Lake Development Biloxi, Miss.

Table 1. Monthly Average Data of TSS and BOD_5 for Duckweed Lagoon System Located at Cedar Grove Development in Biloxi, Mississippi.

Month, 1979	TSS, mg/l			BOD_5, mg/l		
	Aerated Lagoon		Duckweed Lagoon	Aerated Lagoon		Duckweek Lagoon
	Influent	Effluent*	Effluent	Influent	Effluent*	Effluent
May	178	397	10	200	64	20
June	194	176	9	203	67	28
July	420	108	16	138	34	13
August	271	113	8	160	13	10
September	233	132	22	173	20	17
October	173	96	19	171	15	8
November	142	61	11	290	29	10

*Also Influent to Duckweed Lagoon

the raw sewage entering the aerated cell averaged 191 mg/l BOD_5 and 230 mg/l TSS. Average influent and effluent concentrations of BOD_5 and TSS of the second duckweed-covered cell were: influent, 35 mg/l BOD_5; effluent 15 mg/l BOD_5; influent, 155 mg/l TSS; effluent, 14 mg/l TSS. The duckweed coverage on the second cell averaged 2 cm in depth producing an odor free anaerobic system 24 hours a day. The effluent dissolved oxygen concentration was 0.5 mg/l leaving the lagoon, but increased to 5 mg/l after dropping 0.91 m (3 ft) to a drainage ditch.

REMOVAL OF BIOCHEMICAL OXYGEN DEMANDING (BOD) SUBSTANCES BY HIGHER PLANTS

From field studies' data where water hyacinths were grown in domestic sewage lagoons, one can readily see that an additional reduction in BOD is taking place that can be attributed to the plants.[6,8] Because of the nature of most sewage lagoons with their long detention times and complex microbial make-up, controlled laboratory studies are desirable on BOD removal rate to obtain more exact quantitative data. Laboratory studies were conducted at NSTL under wide spectrum growth lights with 14 hour photoperiods in an effort to obtain more exact BOD data. Phenol, an organic chemical, was also used in these studies to further demonstrate the ability of water hyacinths to absorb, metabolize and remove BOD in a similar manner to microorganisms. Domestic wastewater consists of a complex mixture of chemicals including phenol and related organics. The initial volumes of raw sewage or phenol solutions were varied in order to vary the depth and surface to volume ratio. Some containers were left free of water hyacinths as controls to determine the bacterial contribution to BOD removal. In order to assure the same type of bacteria would be present in the controls that were associated with the water hyacinth roots, the plant roots were first dipped in all control solutions for bacterial seeding. Total bacterial counts and 5-day biochemical oxygen demands (BOD_5) were analyzed according to <u>Standard Methods</u>.[10]

Results of these experiments are shown in Tables 2-4. This data indicates that the water hyacinth alone can be expected to reduce BOD_5 of domestic sewage by an average of 1.5 mg BOD_5 per gram of plant mass (wet weight) with liquid detention times of 6 to 7 days. Water hyacinths and microorganisms together can be expected to remove an average of 4.0 mg BOD_5/gram plant mass (WW) with the same detention times.

The ability of water hyacinths to remove BOD_5 produced by other substances such as phenol is demonstrated in Table 4. This data indicates that water hyacinths and microorganisms can remove 3.5 mg BOD_5/gram plant mass (WW) from aqueous solutions in 7 days containing 100 mg/l phenol. The BOD_5 removal due entirely to the water hyacinth was 1.4 mg BOD_5/gram plant mass (WW). These values are consistent with those found with domestic sewage.

These BOD removal rates were achieved with daily growth rates of 3-4%; whereas, field studies have shown average daily growth rates as high as 6% when water hyacinths were grown in sewage lagoons in South Mississippi.[12] The BOD and suspended solids removal rates are not entirely dependent on growth and harvesting rates; whereas the removal of nutrients such as nitrogen and phosphorus is dependent on these variables. The BOD removal rate is dependent on root absorption and metabolic functions; the suspended solids reduction appears to be associated with algae elimina-

Table 2. 5-day Biochemical Oxygen Demand (BOD_5) and Bacteria Concentrations in Raw Sewage With and Without (Control) Water Hyacinths.

Experiment	Fresh Mass WHS, g	Total BOD_5 mg/l			mg BOD_5 removed/ 6 days	mg BOD_5 removed/ g WHs (6 day exposure)	Bacteria, count/100 ml		
		Initial	3rd Day	6th Day			Initial	3rd Day	6th Day
1. w/WHs	1,860	60	---	5	4,070	2.2	8.0×10^5	---	3.0×10^4
2. Control	0	60	---	24	2,664	---	8.0×10^5	---	3.1×10^4
3. Control	0	60	---	35	1,850	---	8.0×10^5	---	2.3×10^4
4. w/WHs	2,140	180	48	9	12,664	5.9	7.7×10^5	1.0×10^4	1.0×10^4
5. w/WHs	2,000	180	36	7	12,802	6.4	7.7×10^5	6.5×10^4	5.0×10^3
6. Control	0	180	100	65	8,510	---	7.7×10^5	3.6×10^4	1.4×10^4

Conditions: Mean Atmospheric Temperature: 22°C

Volume of Raw Sewage: 74 l

Depth: 61 cm

Table 3. 5-day Biochemical Oxygen Demand (BOD_5) And Bacteria Concentrations in Raw Sewage With and Without (Control) Water Hyacinths.

Experiment	Fresh Mass WHS, g	Total BOD_5 mg/l			mg BOD_5 removed 7 days	mg BOD_5 removed/ g WHs (7 day exposure)	Bacteria, Count/ 100 ml		
		Initial	4th Day	7th Day			Initial	4th Day	7th Day
1. w/WHs	306	190	36	20	2040	4.0	TNTC	1.0×10^5	38×10^5
2. w/WHs	429	190	40	20	2040	4.7	TNTC	3.0×10^5	231×10^5
3. w/WHs	413	190	38	21	2030	4.8	TNTC	1.0×10^5	208×10^5
4. Control	0	190	170	85	1260	---	TNTC	1.0×10^5	44×10^5
5. w/WHs	376	112	*30	**21	**1090	**2.9	7.0×10^6	*3.3×10^6	**2.5×10^6
6. w/WHs	412	112	46	18	1130	2.7	7.0×10^6	4.3×10^6	2.7×10^4
7. w/WHs	386	112	42	22	1080	2.8	7.0×10^6	2.7×10^6	1.2×10^5
8. Control	0	112	76	48	768	---	7.0×10^6	*** TNTC	4.5×10^5
9. Control	0	112	69	60	624	---	7.0×10^6	3.1×10^6	3.1×10^6
10. Control	0	112	60	48	768	---	7.0×10^6	2.2×10^6	3.6×10^5

* 3rd day for experiments 5–10

** 6th day for experiments 5–10

*** TNTC - Too numerous to count

Conditions: Mean Atmospheric Temperature: 29°C

Volume of Raw Sewage: 12 l

Depth: 15 cm

Table 4. 5-day Biochemical Oxygen Demand (BOD_5) and Bacteria Concentrations in 100 mg/l Phenol Solutions With and Without (Control) Water Hyacinths

Experiment	Fresh Mass WHs, g	Total BOD_5, mg/l		mg BOD_5 removed/7 days	mg BOD_5 removed/ g WHs (7 day exposure)	Bacteria, Count/100 ml	
		Initial	7th Day			Initial	7th Day
1. Control	0	160	114	184	---	106×10^5	250×10^4
2. Control	0	160	120	160	---	148×10^5	51×10^4
3. Control	0	160	115	180	---	115×10^5	174×10^4
4. w/WHs	155	160	35	500	3.2	110×10^5	61×10^4
5. w/WHs	200	160	37	492	2.5	37×10^5	82×10^4
6. w/WHs	298	160	35	500	1.8	143×10^5	24×10^4
7. Control	0	235	136	396	---	3×10^4	34×10^5
8. Control	0	235	115	480	---	1×10^4	TNTC
9. Control	0	235	116	476	---	2×10^4	---
10. w/WHs	120	235	26	836	7.0	1×10^4	60×10^6
11. w/WHs	242	235	15	880	3.6	1×10^4	3×10^5
12. w/WHs	293	235	29	824	2.8	1×10^4	TNTC

Conditions: Mean Atmospheric Temperature: 29°C

Volume of Phenol Solution: 4 l

Depth: 13 cm

tion prior to discharge.

DESIGN PROPOSAL FOR DOMESTIC WASTEWATER TREATMENT SYSTEMS USING HIGHER PLANTS

Field and laboratory data collected during the past five years at NSTL indicate that a combination of conventional sewage technology and the controlled growth of higher plants such as the water hyacinth and duckweed can produce cost effective, advanced wastewater treatment systems in warm to moderate climate zones. Proposed designs for sewage lagoons using water hyacinths and duckweeds to treat domestic wastewater for small communities of 500 people or less is shown in Figure 2. The same type system for treating wastewater for communities of 1000 to 3000 people is shown in Figure 3. In arriving at the following proposed design characteristics, four problems had to be addressed: (1) sludge accumulation, (2) odor control, (3) BOD reduction, and (4) total suspended solids removal. Nitrogen and phosphorus removal must also be considered if tertiary treatment is required.

In order to minimize sludge handling problems, deep lagoons approximately 3 m (10 ft) in depth, with small surface areas appear to be the most practical method for initial treatment and sludge collection. Deep lagoons receiving raw sewage have advantages and disadvantages. These lagoons act as anaerobic digesters, producing foul odors due to the liberation of hydrogen sulfide gas during the sewage digestion process. Approximately 114g (0.25 lb) of slude per person is generated daily in domestic sewage. The total settled solids in sewage can be reduced by 40-50% and given off as gases if the sludge is anaerobically digested.[11] Yearly sludge accumulation per person after anaerobic digestion is approximately 23 kg (51 lbs). The proposed design in Figure 2 should allow approximately 100 years of operation with 500 people before presenting a sludge removal problem. The design in Figure 3 should operate for approximately 30 years with 3,000 people before sludge removal is needed. Anaerobic digestion for the initial treatment of raw sewage not only reduces the sludge solids, but also reduces the complexity of BOD substances and the concentration of toxic heavy metals when present. Sulfides produced during anaerobic digestion will react with soluble heavy metal ions to form a metallic sulfide precipitate that is relatively insoluble at pH near 7.0. Approximately 1.8 to 2.0 mg of heavy metals can be precipitated as metal sulfides by 1.0 mg of sulfide ($S^{=}$).[1]

In order to eliminate odor emission when anaerobic treatment is used in the first step, it is essential for the first lagoon to contain a photosynthetic aerobic zone, mechanically aerated surface zone, surface sealer, or a combination of these features. The most reliable means of assuring an aerobic surface zone for odor control appears to be the limited use of surface aerators. Studies in Mississippi with the system depicted in Figure 1 have shown that the use of surface aerators during dark hours and photosynthetic algae during daylight hours effectively controls odors with minimum aeration cost. A limited amount of research has been conducted by NASA on the use of duckweed as a photosynthetic surface sealer for small anaerobic lagoons. The use of duckweeds would eliminate the energy requirements of supplemental mechanical aeration. BOD_5 reductions in excess of 70% at hydraulic detention times of 1.2 days in anaerobic ponds was noted by Oswald *et al.*[1] Detention periods of up to 5 days were recommended to compensate for

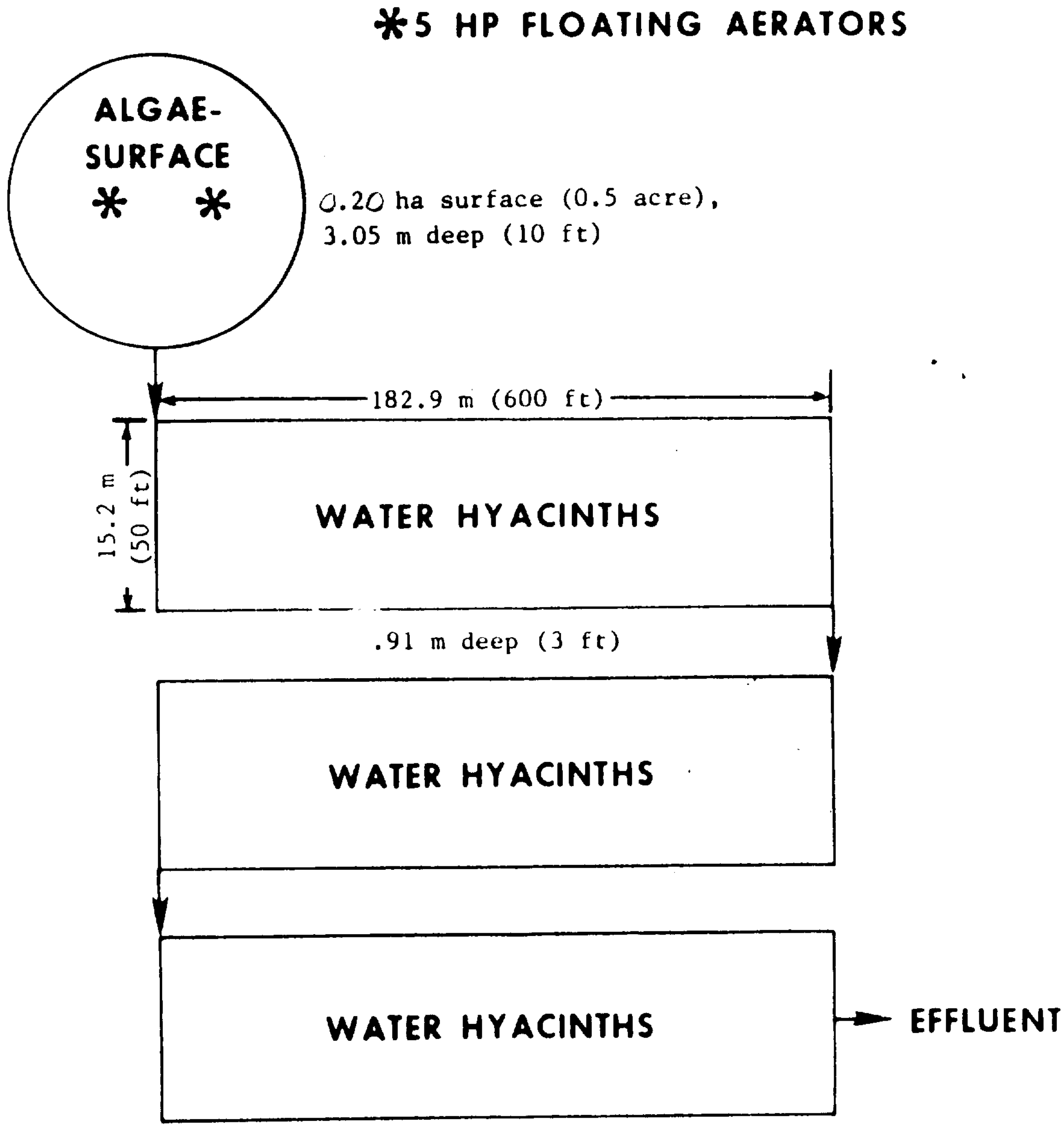


Figure 3. Water Hyacinth Sewage Treatment System Which Will Achieve Secondary to Tertiary Treatment Levels for Wastewater from 1000 ± 3000 People.

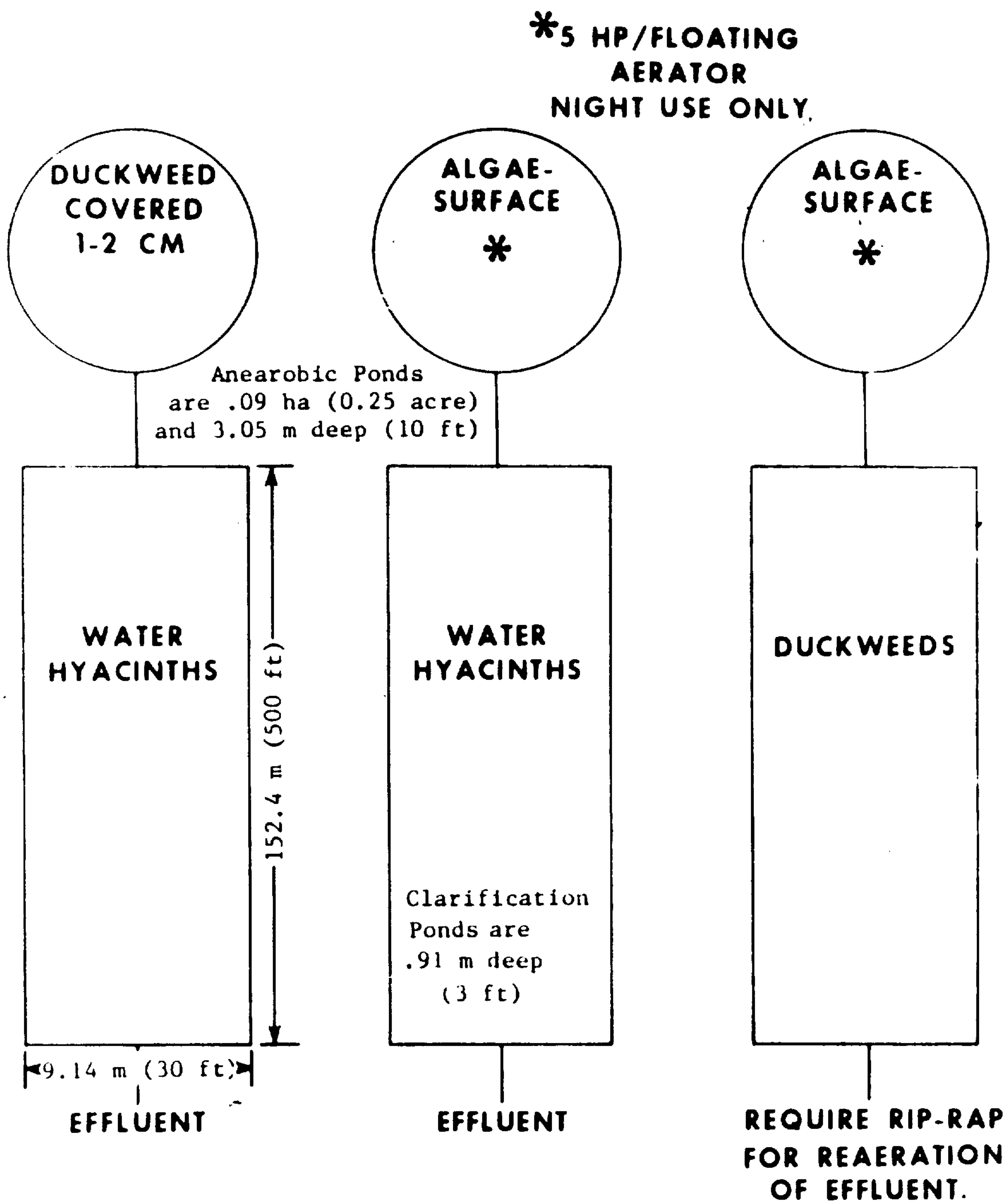


Figure 2. Water Hyacinth, Duckweed and a Combination Water Hyacinth-Duckweed Sewage Treatment Systems Which Achieves Secondary to Tertiary Treatment for Wastewater from 250-500 People.

decreased bacterial activity during cold weather. Detention times of 15 and 5 days are proposed for the anaerobic lagoons in Figure 2 and 3 respectively. When surface aerators are used, additional BOD removal at the rate of 24 kg/ha/day can be achieved.

The designs shown in Figures 2 and 3 are based on influent wastewater containing 150 mg/l BOD_5. These designs assume a 50% BOD_5 removal in the first anaerobic lagoon. Water hyacinth covered lagoons can be expected to remove approximately 1045 kg BOD_5/hectare every seven days or 148 kg BOD_5/hectare/day based on the results of the experiments and field data presented in this paper and an average standing crop of 220 mt/hectare (100 ton/ac).

If tertiary standards must be met, the total nitrogen and phosphorus must be reduced to 3 and 1 mg/l, respectively. Assuming a sewage influent containing 35 mg/l kjeldahl nitrogen and 7 mg/l total phosphorus with a daily increase and harvest rate of 5% plant mass, then the design in Figure 2 should achieve tertiary treatment levels for the waste of 250 people and Figure 3 for 1500 people. This is assuming a standing crop of 220 mt/hectares and a 0.91m (3 ft) depth in the elongated water hyacinth lagoons shown in Figures 2 and 3. Total suspended solid concentrations are reduced by water hyacinth coverage due to shading effects and possibly nutrient reduction.

Plant material harvested from this type system can be processed into usable products. Studies at NASA have shown that the simplest product produced from water hyacinths is compost, a complete plant growth media produced by aerobic decomposition. Plants such as cucumbers, squash, corn, tomatoes, peas, sorghum, etc., have been grown successfully using decomposing water hyacinths as the sole source of soil and food.

Another potential product from the harvested biomass is methane. Methane is produced by anaerobically digesting the fresh plant material. Current experiments at NSTL demonstrate that 0.18 m^3 (6.3 ft^3) of methane can be produced per dry kilogram of plant material in 24 days or less digestion time at 37°C.

An engineering handbook on the construction of vascular aquatic plant wastewater treatment systems will be available by January 1980.

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